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Design and control of radiant heating and cooling systems in Japan: Results from expert interviews

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Abstract

This research conducted investigations of buildings equipped with radiant systems and expert interviews in 2021–2022 with manufacturers and mechanical, electrical, and plumbing (MEP) engineers in Japan who had experience designing radiant heating and cooling systems for non-residential buildings. In total, interviews were conducted with 56 respondents from 16 companies. Results from the building investigation showed that 69% of the identified buildings had radiant ceilings, and 30% had radiant floors. In terms of working fluid, 56% were water-based, and 43% were air-based. For the expert interview, 79% of all respondents answered that the use of radiant systems will continue to increase in the future. In total, 54% of all respondents answered that it has become easier to design radiant systems at present compared to the 2010s. Based on the results, knowledge gaps and challenges in the design of radiant systems were summarized in terms of design method, room temperature control, auxiliary systems, and their relevance to building decarbonization.

Keywords
building decarbonization, expert interview, investigation, practical design, radiant heating and cooling system

1. Introduction

1.1 Background

There is an urgent need to reduce global greenhouse gas (GHG) emissions from the building sector to prevent the further acceleration of global warming. Climate change is a severe problem, with natural disasters causing extensive damage to buildings and cities.[1] Energy and process emissions from buildings in 2021 indicated that the building sector accounts for 33% of the global energy and process emissions.[2] In the last decades, net zero energy buildings[3] and other initiatives have been implemented worldwide to reduce building energy consumption during the operational stage.[4] In addition to reducing operational energy/carbon from the building, there is an urgent need to reduce carbon emissions throughout the life cycle stages, including the manufacturing, construction, use, disposal, and recycling phases of building parts.[5]

One solution to reduce carbon emissions by designing a heating, ventilation, and air-conditioning (HVAC) system might be installing radiant heating and cooling systems (radiant systems). Radiant systems provide cooling/heating by radiation and convection from a cooled/heated surface. Radiant systems are now commonly used as a comfortable, energy-efficient, and resource-effective heating and cooling alternative in buildings.[6] Radiant systems are mainly classified into radiant ceiling panels (RCP),[7] embedded surface systems (ESS),[8] and thermally active building system (TABS),[9] with different characteristics depending on the heat transfer fluid, the radiant surface structure, and the location of the cooled/heated surface.

1.2 Literature review of radiant systems

There are many previous research cases and installations of radiant systems in many countries. Rhee et al.[10] reviewed studies related to radiant systems, which were conducted over a 50-year period until 2015. The results showed that radiant systems have been continuously developed, modified, and improved to achieve better indoor thermal comfort and energy efficiency. Radiant systems can provide the same quality of indoor thermal comfort with a lower air temperature for heating and a higher air temperature for cooling.[11,12] These characteristics are also beneficial to energy efficiency. Hydronic radiant systems with ventilation system can also operate with less airflow than all-air systems, contributing to less draught[13,14] and reducing operational energy due to high-efficiency heat sources and less fan power.

Compared to all-air systems, radiant cooling systems remove heat differently, especially for solar radiation.[15] Previous studies have reported enhanced cooling capacity of radiant cooling systems due to the absorption of solar radiation at cooled surfaces[16–19]; this characteristic has the potential to increase the design flexibility of windows and facades in daylight harvesting spaces. Other research has been conducted from different perspectives, such as control of radiant systems, condensation problems by the moisture air, computational fluid dynamics (CFD), and heat balance simulations.[20] Radiant systems have been adopted in a variety of spaces, such as in office buildings,[21–24] entrance spaces (large spaces),[25,26] and patient rooms.[27]

1.3 Previous research with expert interviews

Previous studies have also conducted surveys and interviews with professionals with substantial experience designing, constructing, and operating radiant systems. In 2016, a committee of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE) released a report from surveys and interviews with mechanical, electrical, and plumbing (MEP) engineers in Japan who had experience designing radiant systems.[28] The survey was developed based on interviews with four experts and distributed to 24 engineers in eight companies (design firms or general construction companies) from 2013 to 2014. Results showed that high initial cost was listed as the primary concern, and humidity control was the second most serious concern in the difficulties and concerns regarding the design of radiant systems. In addition, half or more than half of the engineers involved in recent building projects pointed out the difficulties related to the heat transfer of the radiant system, such as the lack of cooling capacity, slow response time, and control. In 2017, Paliaga et al.[29] interviewed 11 professionals with substantial experience with the design, construction, and operation of embedded radiant systems, especially TABS, in North America, having collectively designed more than 330 radiant cooled buildings. Interviewees had a common understanding that the maximum cooling capacity of TABS is lower than that of air systems but has a self-regulating effect in response to temporal and spatial variations in the room air or radiant surface temperatures. For the ventilation system, a dedicated outdoor air system (DOAS) was used in most cases, and condensation was rarely encountered. The feedback from these MEP engineers is beneficial when exploring and determining the next research topics for radiant systems in the future.

1.4 Objective

The objective of the current study was to investigate design and control strategies currently used for radiant systems in Japan, highlight themes of common practice and variations in practical approaches, and identify research areas that serve practitioner needs. The current study builds on the investigation and expert interviews conducted by SHASE from 2013 to 2014.[28] In the 2010s, net zero energy buildings rapidly became popular in Japan, and the number of radiant systems installations increased yearly. In more recent years, buildings have started to be evaluated with new scopes such as whole life carbon (building decarbonization)[30–32] and building resilience.[33] In order to respond to these changes, expert interviews and surveys were conducted again to find out what engineers have required and still require in the research of radiant systems, and what new issues are being raised.

2. Methods

Figure 1 shows the methodology for installation survey and expert interview in this study. This research consists of two parts, that is, investigation of buildings equipped with radiant systems, and a collection of expert feedback through interviews and questionnaires.

2.1 Investigation of buildings in Japan with radiant systems

A database of non-residential buildings with radiant systems was compiled based on data provided from two radiant system manufacturers in Japan and papers published in the Architectural Institute of Japan (AIJ)[34] and SHASE.[35] Data on the building use, the year of completion, and the type of radiant system were collected. The manufacturers were members of The Association of Radiant Cooling and Heating systems of Japan (ARCH)[36] and cover a large share of radiant systems in non-residential buildings in Japan. Radiant systems were classified by radiant surface position, heat transfer fluid, and structure. In this study, radiant surfaces were classified into the ceiling (including TABS) and the floor. The heat transfer fluid was classified into water and air. Note that this study only classified embedded surfaces or panels by the structure. The structure of radiant surfaces, that is, “with or without insulation” and “duct or chamber” (only for air-based), was asked but not used in this study. The following types of radiant systems were excluded in this study: electric panel heaters, radiant cooling walls, and floor heating systems in residential buildings.

2.2 Expert interviews and questionnaires

Interviews were conducted either face-to-face or via online meetings. After the interview, the investigators asked respondents to share a questionnaire link with their colleagues. In total, responses from 56 engineers working in 16 different companies (8 design firms, 6 construction companies, and 2 manufacturers) from July 2021 to June 2022 were obtained. Interviews were conducted with 32 engineers, and 31 engineers responded to the web questionnaire. There were seven that cooperated in both the interview and the questionnaire, resulting in a total of 56 respondents. Some of the questions were the same in the interview ($n = 32$) and in the web questionnaire ($n = 31$). In these cases, the duplicate responses were removed, prioritizing the results from the interview. In the interview and web questionnaire, engineers were asked about the characteristics of radiant systems which they have designed and installed in the building (radiant surface, heat transfer fluid, building use, auxiliary system, and combination with renewable resource). The survey also looked at the impact of the global movement toward building decarbonization and the respondents' future outlook for radiant systems. In the web questionnaire, some questions were asked in the same way as the SHASE report[28] so that the results could be compared with that of 2010s.

3. Results from the Investigation of Buildings with Radiant Systems

Figure 2 shows the number of buildings with radiant heating and cooling systems in Japan in the past 20 years. A total of 661 buildings with radiant heating and cooling systems were

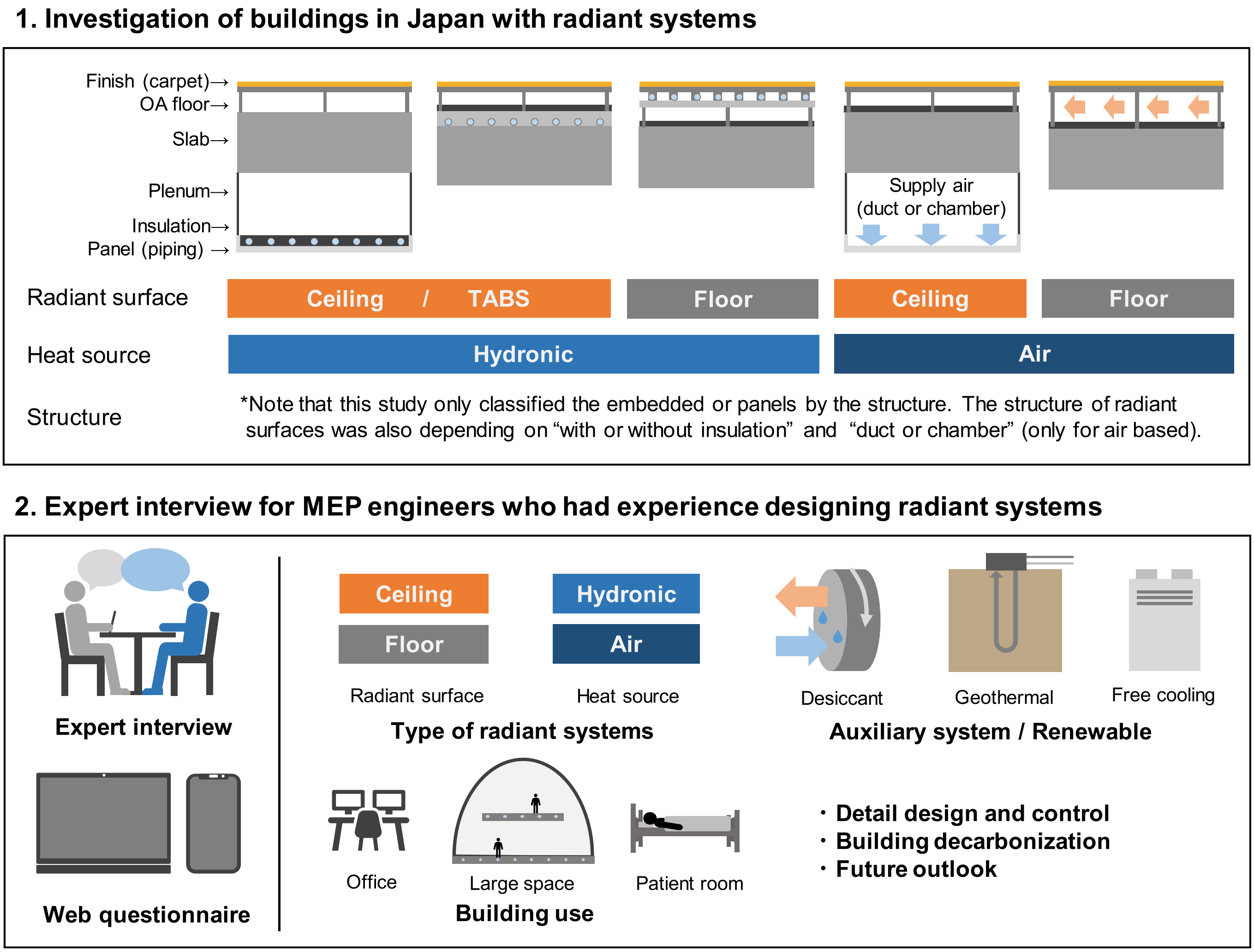

FIGURE 1 Investigation of buildings in Japan with radiant systems and expert interview in this study

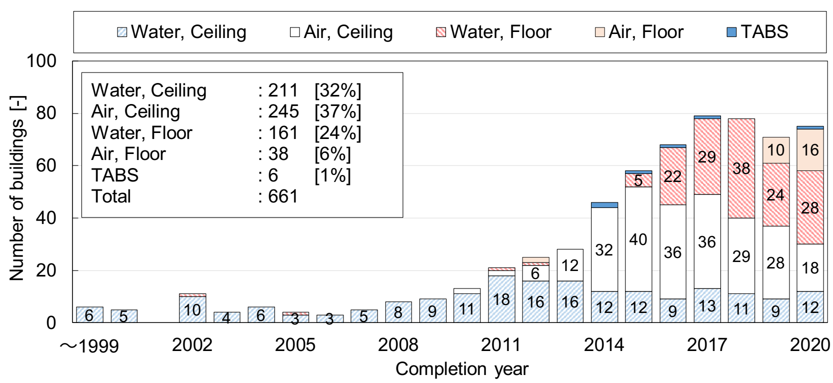

FIGURE 2 Buildings in Japan with radiant heating and cooling systems

collected. If a building had a radiant system in any of its rooms or zones, it was counted as one building, regardless of the installed surface area. The buildings were grouped by the heat transfer fluid and radiant surface primarily used in each building. Air-based radiant floor systems are similar in configuration to underfloor air distribution systems but designed so that the plenum air indirectly cools/heats the surface temperature before being supplied to the room.

Radiant ceilings were installed in 69% of the buildings, and radiant floors were installed in 30%. In terms of heat transfer fluids, 56% were water-based, and 43% were air-based. Before 2010, the number of installations each year was less than 20, but after 2010, the number of installations increased up to 79 projects in 2017. In particular, the percentage of air-based radiant ceiling and water-based radiant floor constructions have increased since 2010. In addition, there was a constant demand for water-based radiant ceiling every year. In some buildings, air-based systems were chosen over hydronic systems to avoid potential water leakage in the room. Hydronic floor systems were commonly used in highly glazed spaces such as entrance halls, due to its high performance when exposed to direct solar radiation.[37,38]

Since 2017, the number of installations of the radiation system had remained between 70 and 80 projects. The number of radiant systems installed has not changed much recently in Japan. However, radiant systems have an advantage that they use less high-global warming potential (GWP) refrigerants compared to packaged air systems. Considering that regulations regarding refrigerant leakage are likely to become stricter in the future,[39] radiant systems may be installed in even more buildings. With about 10 000 new office buildings being constructed in Japan each year,[40] there is a potential for even more buildings to be implemented with radiant systems in the future.

4. Results from Expert Interviews and Questionnaires

4.1 Questions common across interviews and questionnaires

Table 1 shows the outlook on the future installation of radiant systems in buildings. Excerpts of comments corresponding to each response group were listed as reference. In total, 79% of all respondents indicated that the use of radiant heating and cooling systems would "increase" or "partially increase." One of the reasons for the "increase" was that radiant systems can provide both energy saving and thermal comfort. Many respondents indicated that the future installation of radiant systems would be limited to specific building uses/rooms, such as patient rooms and office buildings. Many MEP engineers pointed out the high initial cost of radiant systems, regardless of their answer. Some MEP engineers mentioned that designing radiant systems requires advanced design with understanding of its characteristics.

Table 2 shows the responses on whether designing radiant systems have become easier or more difficult compared to the 2010s, when the survey by SHASE was carried out. More than half (54%) of the respondents answered that it is easier to design radiant systems at present compared to the 2010s. Some engineers indicated that the increased number of building projects with radiant systems made it easier for them to reference and design. Furthermore, radiant systems have been added to the Building Equipment Design Standard of the Ministry of Land, Infrastructure, Transport, and Tourism in Japan[41] in 2015. In 2017, the national standard of radiant ceiling panels (ARCH[36]) was developed. The development of national standards and guidelines was one of the reasons many respondents answered that it has become easier to design.

Table 3 shows the respondents' view of whether building decarbonization will have an impact on the installation of radiant systems. When "high impact" and "low impact" responses were merged, 53% of all respondents answered that building decarbonization would have an impact on the installation of

TABLE 1 Outlook on future installation of radiant systems

Question: What is your outlook of the number of radiant systems that will be installed in the future?

Response	Number of respondents $N = 56$	Comments
Increase	16 (29%)	• Radiant systems can provide both energy savings and thermal comfort. • Internal gain has decreased due to reduced equipment gain (conversion to laptop computers) and building envelope performance has improved. • More real estate developers are willing to install radiant if the initial cost could be lowered.
Partially Increase	28 (50%)	• Because of the high initial cost, the installation of radiant systems is expected to increase slightly only for specific applications (entrance rooms, large spaces) and for rooms where thermal comfort is especially important. • For draft-sensitive spaces (e.g., patient rooms), the installation of radiant systems is expected to increase
No change	8 (14%)	• High initial cost • Requires advanced design with an understanding of the characteristics of radiant systems (e.g., handling the heat load of perimeter zones and the use of separate sensible and latent cooling systems)
Decrease	3 (5%)	–
No answer	1 (2%)	–

TABLE 2 Responses on whether designing radiant systems has become easier or more difficult compared to the 2010s

Question: Has it become more difficult or easier to design radiant systems compared to the 2010s?

Response	Number of respondents $N = 56$	Comments
More difficult	1 (2%)	• Clients are becoming more cost-conscious than before, and it is becoming more difficult to install radiant systems due to high initial costs.
No change	12 (21%)	–
Easier	30 (54%)	• The number of buildings with radiant systems is increasing, and they are becoming more common as one of the HVAC systems. • Manufacturers have established their technologies, and there are no longer any special concerns, regardless of whether water-based or air-based radiant systems are used. • Compared to the past, it is now easier to design radiant systems, as radiant systems are now listed in the Building Equipment Design Standard of the Ministry of Land, Infrastructure, Transport, and Tourism in Japan.
No answer	13 (23%)	–

TABLE 3 Respondents' view of whether building decarbonization will have an impact on the installation of radiant systems

Question: How much do you think building decarbonization would impact the installation of radiant systems?

Response	Number of respondents $N = 56$	Comments
High impact	8 (14%)	• Radiant systems are becoming a powerful item for achieving a carbon neutral building. • Because of the limited energy savings by all-air systems, radiant systems are definitely one of the key technologies to achieve building decarbonization. • Radiant system can use low exergy heat sources, making it easier to use renewable resources, which is more compatible with decarbonization.
Low impact	22 (39%)	• I doubt that the radiant system is beneficial in terms of life cycle carbon emissions (LCCO2). • The reduction of distribution energy (fans, pumps) in radiant systems are effective for reducing running costs (operational carbon), so there will be a certain impact.
No change	13 (23%)	• I do not consider radiant systems to have any notable advantages in energy saving. • The installation of radiant heating and cooling does not directly lead to energy efficiency of the building. Appropriate design of the entire system is a prerequisite, such as improving the coefficient of performance (COP) of the chiller and designing an auxiliary system.
No answer	13 (23%)	–

radiant systems. Respondents who answered "high impact" indicated that radiant systems are becoming a powerful item for building decarbonization to reduce operational energy and carbon emissions. Other respondents expressed doubts whether radiant systems would be beneficial in terms of whole life carbon. This doubt is due to the fact that radiant systems use materials with high carbon footprints (e.g., aluminum for radiant panels).[31,32] One of the respondents who answered "no change" indicated that an appropriate design of the entire system is a prerequisite for achieving carbon neutrality, such as improving the coefficient of performance (COP) of the chiller and designing an auxiliary system.

4.2 Response from questionnaires

Figure 3 indicates auxiliary systems and renewable resources that were preferred in combination with radiant systems. Answers were obtained from 10 respondents in 2014 and 31 respondents in 2022, respectively. Respondents were shown a list of choices, and multiple selections were possible. One of the reasons for the particularly high percentage of desiccant technology in both 2014 ($n = 6$) and 2022 ($n = 20$) was that dehumidification is essential to avoid condensation at radiant surfaces during the summer season in Japan, which becomes hot and humid. Natural ventilation had a few responses for both 2014 and 2022, and the reason was expected to be the difficulty in controlling window opening and radiant surface temperatures to avoid condensation.

Figure 4 shows that the challenges and difficulties in designing radiant systems. Answers were obtained from 24 respondents in 2014 and 31 respondents in 2022, respectively. Respondents were shown a list of choices, and multiple selections were possible. The category with the highest response rate was "L: high initial cost," both in 2014 ($n = 20$) and 2022 ($n = 23$). For both 2014 and 2022, categories "B: slow response time" and "C: response to fluctuation and uneven distribution of cooling load" were selected by 40%–50% of the respondents. In total, 40% of the respondents in 2022 expressed concerns in terms of condensation and humidity control (categories "G: latent heat removal, humidity control" and "H: preventing condensation"), though the percentages of respondents decreased from that of 2014. The number of respondents who answered "I: control" decreased from $n = 6$ in 2014 to $n = 2$ in 2022. This is likely due to the knowledge and experience accumulated over the years, as pointed out in Table 2.

Table 4 shows the knowledge gaps in designing radiant systems. Answers were obtained from 24 respondents in 2014 and 31 respondents in 2022, respectively. The respondents selected their answers from the given items. For the lack of design guidelines, recommended design values, and design methods for radiant systems, four respondents in 2014 and nine in 2022 answered. One of the respondents was unsure about whether to control based on room temperature or surface temperature, and how to compensate for the low circulating air volume. The REHVA[12] guideline and ISO 11855[42] for radiant heating and cooling systems describes how to control radiant systems based on room temperature. These standards and guidelines recommended that it is preferable to control based on the operative temperature in the occupied area. Previous studies have investigated the optimal position, shape, size, and color of the room temperature sensor to express heat transfer between sensor and space similarly as for a person.[12,43–46] For the knowledge gaps related to the effects of radiant systems on the human body, and occupant thermal comfort, many engineers indicated that there was a lack of general knowledge about radiant systems with thermal mass, such as TABS. One of the reasons could be that there are currently no TABS guidelines for Japanese design practices (e.g., preparing for an earthquake, combination with raised floor). However, it must be noted that the ISO 11855 standard provides a method for evaluating the indoor comfort of Tables,[47] as well as design and sizing methods.[48] There was also a request for guidelines on how to determine the indoor setpoint for radiant systems, in contrast to the conventional all-air systems.

4.3 Qualitative response from interviews

Figure 5 shows an overview of the qualitative feedback from the expert interviews. In addition to the previous questions, the qualitative feedback on radiant systems obtained from engineers and manufacturers was summarized by topic. Several respondents pointed out that installing a radiant system with an auxiliary system would result in a high initial cost. Respondents highlighted the challenges in adopting radiant systems if the clients were not convinced of the high initial cost. Another potential limitation that was raised was the fact that radiant

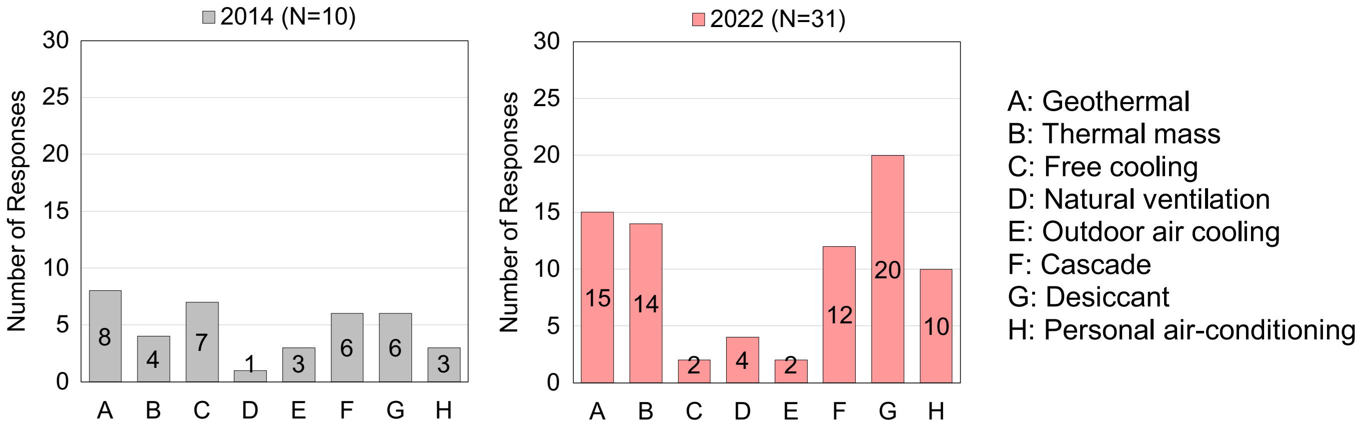

FIGURE 3 Auxiliary systems and renewable resources that were preferred in combination with radiant systems

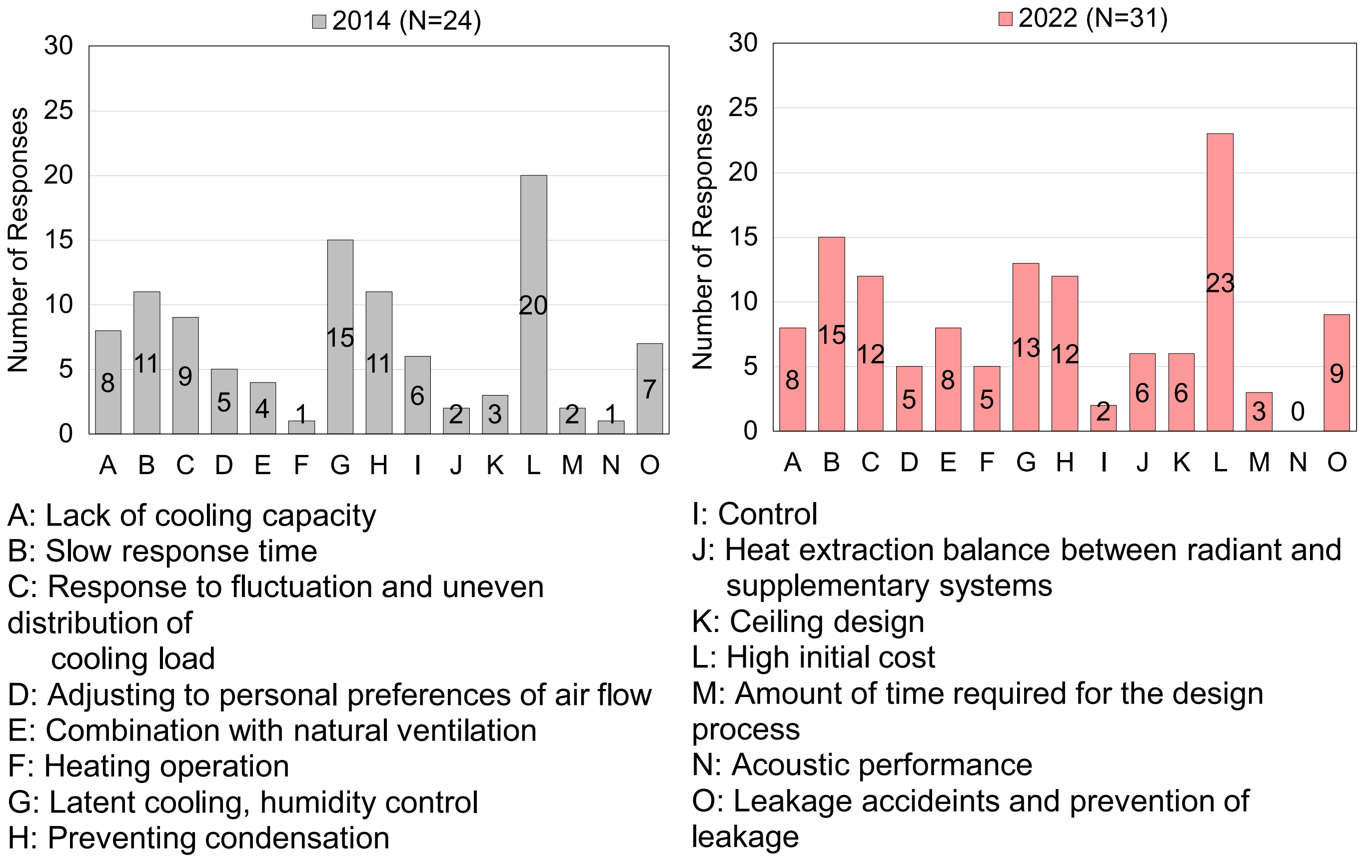

FIGURE 4 Challenges and difficulties in designing radiant systems

systems were not listed among the technologies supported by the ZEB subsidy program from the Ministry of Economy, Trade, and Industry.[49] From manufacturers' point of view, high upfront carbon emission and increasing cost of aluminum for the radiant panels were raised as major difficulties in promoting the use of radiant systems. Potential alternatives to aluminum, in terms of cost and carbon emissions, are being considered.

In terms of HVAC-related issues, dehumidification was mentioned as a crucial topic for designing any HVAC system in a hot and humid climate like Japan. Since a radiant system cannot handle latent heat, dehumidification technologies such as a desiccant system are required. It is necessary to examine the ventilation system design together with the radiant system in terms of the heat removed by each system. Another challenge in the design of radiant cooling systems in hot climates is their limited cooling capacity. Installing active chilled beams and high-efficiency heat pumps was mentioned as an effective way to solve the problem of high perimeter loads in hot and humid summer climates like Japan.

From the perspective of architectural design and planning, the respondents also pointed out the need for additional

TABLE 4 Knowledge gaps in designing radiant systems

Question: What do you think are the knowledge gaps in designing radiant systems?

Response	Number of respondents $N = 24$ (2014)	Number of respondents $N = 31$ (2022)	Comments (2022)
Design guidelines, recommended design values (indoor environmental conditions/panel surface temperature), and design method for radiant systems	4 (17%)	9 (29%)	• There are many examples of heating, such as floor heating, but it would be good to have more design guidelines for cooling. • Until a few years ago, a certain manufacturer had a well compiled design guideline, but the current status is unknown. • Whether to control by room temperature or surface temperature, how to compensate low circulating air volume, etc.
Effects of radiant systems on the human body, occupant thermal comfort, etc.	5 (20%)	12 (39%)	• It is difficult to evaluate thermal comfort for radiant wall systems. • Fluctuation of heat flux in case of TABS. • There are no design guidelines of radiant systems for indoor thermal comfort, so there is still a need to verify indoor thermal comfort in the operation phase through field measurement.
Heat flux and the indoor environment when radiant systems are in operation	5 (20%)	3 (10%)	• Radiant systems should have a different setpoint temperature compared to all-air systems, but because there are no standards, there is a tendency for operators to overcool or overwarm the indoor environment. • Dynamic thermal performance of TABS, including its heat transfer, are very difficult to predict. • The large thermal capacity of concrete may make it difficult to find a control method.

adjustment to fit the systems (e.g., floor design and header installation). Furthermore, the large number of piping connections of radiant systems poses a higher risk of water leakage and therefore special attention needs to be given to vibration and shocks from earthquakes. Some engineers also pointed out the acoustic issue of radiant ceiling panels. At high coverage ratios of radiant ceiling panels, some office workers complained about sound reverberation, which is also a commonly known issue for radiant ceilings.[50,51] The lack of flexibility in changing the layout of radiant systems were pointed out as a barrier, especially in tenant offices. According to the Japanese building regulation, HVAC systems need to be fully installed upon handover. Depending on the layout of the tenant spaces, the HVAC systems may need to be renovated, which would be a disadvantage for radiant systems considering the higher cost in installing the system.

5. Discussion

Investigation of buildings equipped with radiant systems and expert interviews and questionnaires were conducted to identify what engineers require to design radiant systems and to investigate any new issues or perspectives in practice. Hence, topics that were commonly discussed in the questionnaires and interviews were summarized below.

5.1 Country-specific factors

Within the identified buildings, there were less than 10 buildings with radiant systems each year before the 2010s, but since 2016, radiant systems were installed in 60 to 80 buildings per year. Since the 2010s, the number of net zero energy buildings in Japan has been increasing, and this is may have contributed to the increase in the installation of radiant systems. Many MEP engineers pointed out the high initial cost of radiant systems regardless of the interview period (2014 or 2022). This suggests the need of case studies comparing the initial and operating costs to promote the further installation of radiant systems.

This study showed that air-based radiant systems were installed in 43% of the total in the past 20 years. These air-based systems are also easier to deal with humidity control. In Japan, where earthquakes often occur, water-based radiant systems are sometimes avoided because of the risk of water leakage. Embedding TABS piping directly into the structure of the building is also not common in Japan in terms of maintenance, replacement, and the risk of water leakage by earthquakes. Based on the discussion above, air-based radiant systems are expected to be in constant demand in the future.

5.2 Difficulty of designing radiant systems

From the interview survey, more than half of the MEP engineers answered that it was easier to design radiant systems compared to the 2010s. The publication of the standard of radiant ceiling panels and the increase in case studies have helped to design and control radiant systems more easily. The decrease in internal heat gain of the building due to the widespread use of light-emitting diode (LED) lighting[52] and laptop computers[53] has also contributed to the increase in the installation of radiant systems. Studies documenting the benefits and limitations of the desiccant dehumidification system and coupling of the radiant system with renewable sources have helped in the broader use of radiant systems as well. Compared to the all-air system, which typically uses a chilled water temperature of 7°C, radiant systems have the potential to use chilled water of 16 to 20°C for cooling, which is compatible

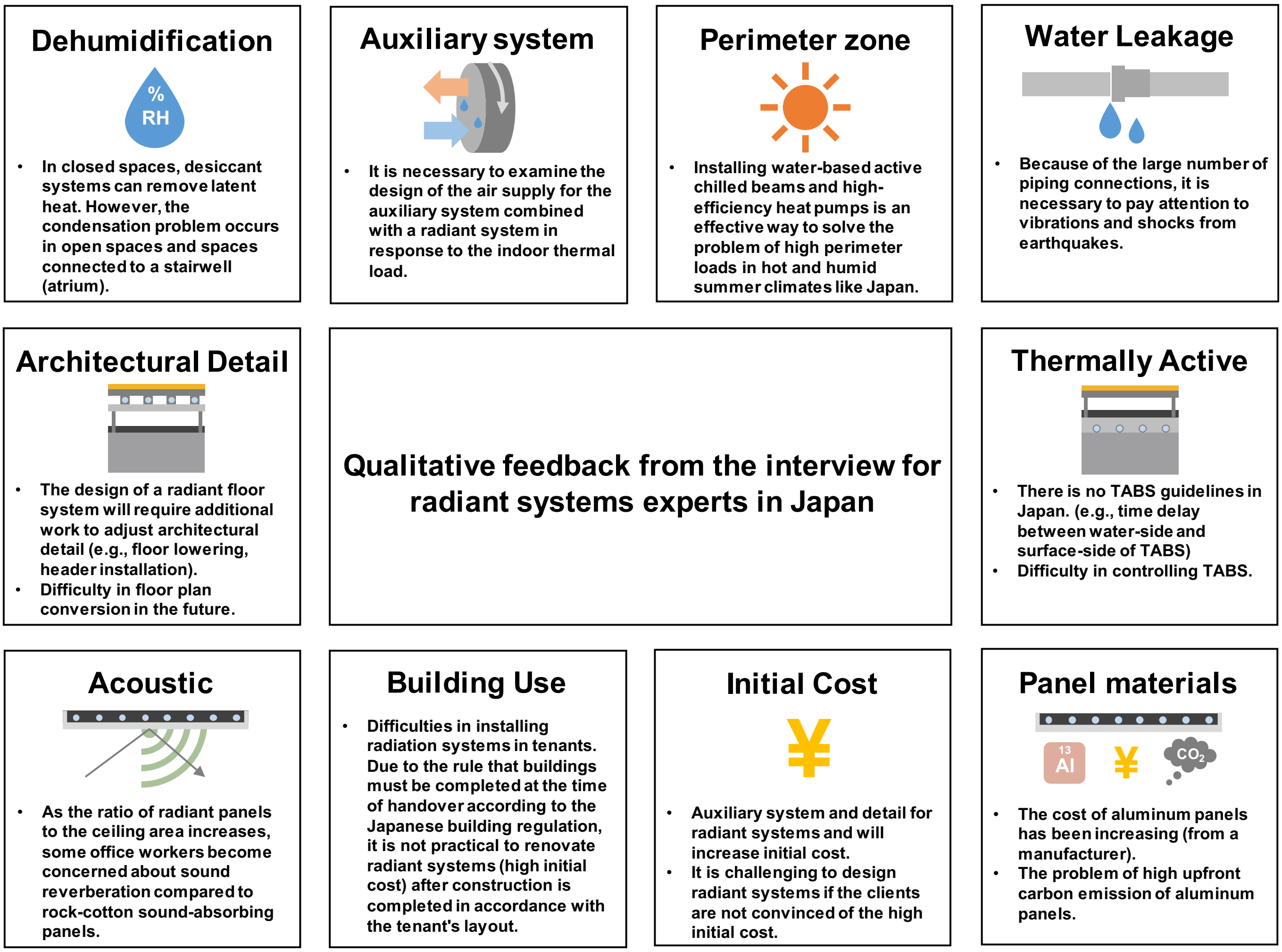

FIGURE 5 Qualitative feedback from the interview for radiant systems experts

with renewable sources, such as well water and geothermal heat. One research conducted a comparative case study of radiant ceiling panels that use well water and the potential for their installation in Japanese office buildings in different regions.[54] The results showed that more floor area could be cooled with well water as the heat source, in areas with cooler outdoor climates.

As shown in Table 4, many MEP engineers commented on the knowledge gap in the research area of the thermal mass of the building represented by TABS. Radiant ceiling panels and radiant floor systems were reported to be relatively easy to design and size because the manufacturers' catalogues describe the heating and cooling capacities under standard conditions. On the other hand, it is difficult to determine how much heating and cooling capacity to expect from TABS. The heating and cooling capacity also depends on the facade, the structure of the radiant surface, and the occupancy behaviors. It would be beneficial to develop national guidelines and calculation tools for TABS to bridge the gap between research and practice, and implement them in building energy codes.

5.3 Building decarbonization and radiant systems

There were also many comments on the topic of building decarbonization, which was not present in the survey conducted in 2014. There were divided opinions among the respondents on whether radiant systems perform well in terms of whole life carbon. One research conducted a comparative case study of the whole life carbon of a radiant system and an all-air system in a non-residential building.[55] Results showed that implementing TABS reduced operational carbon (−0.75) and increased embodied carbon (+0.21) compared to a packaged variable air volume system. Although implementing TABS could lower the floor height, reduce ducting, and downsize the HVAC equipment, installing the pipework for TABS resulted in an increase in the total embodied carbon in this case study. Similar comparisons should be considered in Japan, as calculation boundaries are different for each country, for example, carbon emission factors for electricity and gas, selection of life cycle modules, accounting for refrigerant leakage,[56] and climatic conditions. The development of radiant systems using low upfront carbon emission materials would also be necessary.

6. Conclusion

The objective of the study was to examine the current trend in the design and control of radiant systems in practice in Japan. An investigation of existing buildings and expert interviews and questionnaires were conducted from 2021 to 2022. The conclusions are as follows:

- In Japan, as of 2020, 661 buildings were found to be equipped with radiant systems. Radiant ceilings were installed in 69% of the buildings, and radiant floors were installed in 30%. In terms of the heat transfer fluid, 56% of the buildings had water-based radiant systems, and 43% were air-based.
- In total, 79% of all respondents answered that the use of radiant systems will continue to increase in the future.
- In total, 54% of all respondents answered that it has become easier to design radiant systems compared to the 2010s, due to the development of national standards and guidelines and the increased number of implementations in new building projects.
- The most preferred auxiliary systems in combination with radiant systems were the desiccant system. One of the reasons is that dehumidification is essential to avoid condensation during the summer season in Japan, which becomes hot and humid.
- From the quantitative investigation of buildings in Japan with radiant systems and expert interviews, the design method and practice of radiant systems have gradually become more widespread in non-residential buildings in Japan.
- The high initial cost of radiant systems remains to be one of the major obstacles in adopting radiant systems. Further studies on the operational cost and added values of radiant systems are required to convince clients to adopt radiant systems.
- The development of national standards and guidelines was mentioned as a contributor to an easier design of radiant ceiling panels, and the lack of them as a barrier to implementing TABS. Practitioner-oriented tools and national guidelines, as well as the implementation in building codes, could enable radiant systems to be a more common HVAC solution.

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Disclosure

The authors have no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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